A new Leafiness-LiDAR index to estimate light interception in intensive olive orchards

L. Sandonís-Pozo[1*], J.A. Martínez-Casasnovas[1], A. Escolà [1], J.R. Rosell-Polo[1], J. Rufat[2], M. Pascual[3].
[1] *Research Group in AgroICT and Precision Agriculture (GRAP), Universitat de Lleida/Agrotecnio-CERCA Center, Catalonia, Spain*
[2] *Research group in Efficient Use of Water in Agriculture, Institute of Agrifood Research and Technology, Lleida, Catalonia, Spain*
[3] *Department of Horticulture, Botany and Gardening, Universitat de Lleida, Catalonia, Spain*
* leire.sandonis@udl.cat

Abstract

Canopy light interception constitutes an important yield limiting factor in high density olive orchards. However, its characterisation still implies laborious measurements. A new index, the Leafiness-LiDAR index (LLI), is presented as a LAI estimator. LLI combines LiDAR-derived parameters: Cross-Section and Leafiness from 3D point clouds. To validate the results, photosynthetically active radiation (PAR) measurements, canopy volume, yield and quality parameters were collected and analysed. LLI showed significant correlations both with PAR and canopy volume (r = 0.8) and quality parameters (r = -0.6). LLI may be useful as an early decision canopy monitoring tool in the framework of Precision Fructiculture.

Keywords: LiDAR, canopy, light-interception, photosynthetically active radiation (PAR), intensive olive orchards.

Introduction

Olive (*Olea europaea* L.) cultivation in intensive and super-intensive systems is growing worldwide and especially in the Mediterranean Basin (Zipori et al., 2020). In these systems, the canopy light interception constitutes an important yield and quality limiting factor (Reale et al., 2019). Particularly, canopy sunlight use efficiency affects flowering, fruit set, fruit colour, size, chemical composition and quality of fruits, being directly related to the effect of nutrition, irrigation and pruning (Gómez-del-Campo and García, 2012; Proietti et al., 2012).

Regarding high-density (HD) and super-high-density (SHD) planting systems, factors such as hedgerow size and planting geometry have a dominant effect on light conditions (Rosati et al., 2021). In traditional orchards, olive tree canopies are generally optimally illuminated since the planting system is low density and individual trees are highly pruned to maintain an adequate leaf area (Acebedo et al., 2000). However, in HD and SHD olive systems, as plant density increases, the orchard structures that ensure high interception generate excessive shading on canopy trees along the rows (Connor et al., 2014). Furthermore, fruits are not distributed regularly within the canopy. Most of the olives appear at the canopy periphery, where illumination is higher than in the interior. Due to this reason, some fruit characteristics, such as size and oil content are significantly different according to their position in the canopy (Acebedo et al., 2000; Connor et al., 2009).

Therefore, one of the main challenges in modern fructiculture is to improve light penetration and distribution within the canopy, to maximize the exposure of fruiting sites. The challenge requires adequate management of the canopy by establishing the optimum width of hedgerows for maximum yield while reaching a balance between vegetative development and productivity (Cherbiy-Hoffmann et al., 2013). Some studies were found in the scientific literature that made simulations to improve canopy illumination in olive trees. Gómez-Del-Campo and García (2012) tried various combinations of hedgerow height, width, slope and spacing to maximize well-illuminated productive canopy area. Connor (2006) proposed modelling crop structures considering vegetative growth, flower density, fruit set, and fruit dry weight as a function of photosynthetically active radiation (PAR). The main target was finding a critical PAR threshold to combine appropriately high PAR interception and high fruiting.

Leaf area index (LAI) and PAR are two biophysical parameters that are closely related and often measured and validated together in the field (Schaefer et al., 2015). Specifically, in SHD and HD orchards, PAR interception and distribution within the canopy is related to LAI (Connor et al., 2014), being a key input to plan crop management tasks such as pruning or fertigation. Traditionally, PAR has been measured to estimate the LAI by using ceptometers. However, ceptometer-based measurements require direct sunlight and present limitations with diffuse light conditions. (Pokovai and Fodor, 2019). For that reason, it is difficult to replicate PAR measurements in a continuous way and that compromises their use in a Precision Agriculture context.

In this respect, LiDAR-based Mobile Terrestrial Laser Scanning (MTLS) are not dependent on light conditions and could be a possible solution to overcome that problem. MTLS have been widely used to estimate canopy density and LAI measurement (Arnó et al., 2013; Kargar et al., 2019; Mahmud et al., 2021). Furthermore, it allows geometrical and structural canopy parameters to be obtained along the entire season (Escolà et al.,2017). The objective of this work was to assess the correlation between the new Leafiness-LiDAR Index and the LAI. LLI was obtained from the combination of geometrical and structural parameters extracted from MTLS-derived 3D point clouds, as an alternative to ceptometer measurements to estimate LAI. Also, to validate the results, the correlations between PAR, LAI, canopy volume, yield and quality-related parameters were assessed to compare both PAR and LLI relationship with those parameters in HD training systems.

Materials and methods

Study area and experimental design

The experiment was carried out in an HD olive orchard (*Olea europaea* cv. Arbequina, with 1010 trees ha^{-1}), located in Torres de Segre, Catalonia, Spain (X = 296 975 m, Y = 4 599 900 m UTM 31T/ETRS89). The orchard had an area of 2.5 ha and consisted of 16 NE-SW oriented rows (Figure 1). The experimental design was a completely randomized block (4) with 56 experimental plots. Each experimental plot consisted of six trees in which suboptimal (N0) and sufficient N dose rates (N50) were crossed with different irrigation dose rates (from deficit conditions in different periods to full irrigation) in order to increase the canopy size variability. To avoid the edge effect, only the four central trees of each plot were considered for the experiment. The maximum tree height and width were approximately 3.75 m and 2 m, respectively.

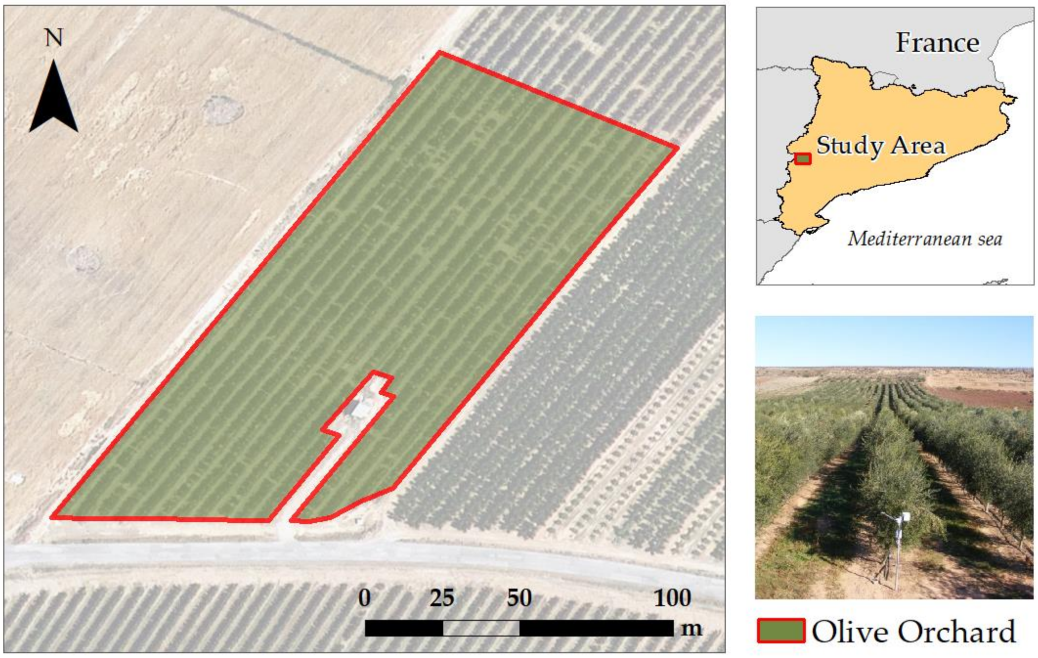

Figure 1. Location and perspective view of the experimental olive orchard.

LiDAR data acquisition and extraction of geometric and structural parameters

LiDAR data were acquired in 15th July 2013 by means of a UTM30-LX-EW sensor (Hokuyo Automatic Ltd., Osaka, MTLS based on a Japan), with a measurement range of up to 30 meters in a 1000 lux environment The scan angle was 270° and the scan frequency was 40 Hz, with an angular resolution of 0.25°. The sensor was located at a distance of 2 m above the ground. A GNSS-RTK GNSS1200 receiver (Leica Geosystems AG, Heerbrugg, Switzerland) was used to georeference the sensor position and self-developed algorithms were used to create a 3D point cloud with absolute coordinates. Canopy geometrical and structural parameters were derived from the 3D point cloud (Table 1). For that, the cloud points were summarized every 0.1 m along the tree following the methodology explained in Escolà et al. (2017) and, later on, averaged to obtain a single value per experimental plot.

Table 1. Description of the geometric and structural vegetation parameters extracted from the MTLS point cloud each 0.1 m along the tree rows.

Parameter	Abbr.	Description
Maximum Height (m)	MH	Maximum height of the canopy every 0.1 m along the rows.
Maximum Width (m)	MW	The width of the canopy is calculated as the average of the maximum widths every 0.1 m in the vertical plane and every 0.1 m along the rows.
Cross-Section (m^2)	CS	The Cross-Sectional area of the canopy is the product of MH and MW.
Porosity	P	Ratio of the number of laser beams trespassing the canopy (Bi) by the total beams emitted from the LiDAR sensor (Bt) every 0.1 m along the rows.
Leafiness	L	Ratio of the number of intercepted laser beams by the total beams emitted from the LiDAR sensor every 0.1 m along the

	rows. This percentage was calculated as the inverse of Porosity (P). (1)

$$L= (1 - P); L= \left(1 - \frac{Bi}{Bt}\right) \qquad (1)$$

Leafiness-LiDAR index (LLI) calculation

The sunlight use efficiency is controlled by a balance between the photosynthetic capacity of the tree (linked to LAI) and the canopy illumination exposure. Regarding olive orchard management, this balance is very important since a leafy tree/hedgerow but with low porosity could diminish the canopy light use efficiency, while a porous tree with few leaves could diminish the photosynthetically capacity of the canopy (Cherbiy-Hoffmann et al., 2013).

Here, a new index to parametrize the hedgerow in terms of yield and performance is proposed. Its name is Leafiness-LiDAR Index (LLI) (2) and refers to the ability of the hedgerow to intercept light. This index was calculated as the product of the canopy Leafiness and its Cross-Sectional area.

$$LLI=L*CS \qquad (2)$$

Where the LLI is expressed in m^2 since the Leafiness (L) was considered as a dimension 1 ratio and the Cross-Sectional area (CS) is expressed in m^2.

Measurement of PAR, olive yield and oil quality data acquisition

An Occupier Ceptometer LP-80 (Decagon Devices, Inc. Pullman, WA, USA) was used to measure PAR values on each experimental plot in 15th July 2013. Each value was calculated as an average of 80 sensor cells for every 4 individual readings taken transversely to the hedgerow at soil surface level (two positions on each side of the olive hedgerow). At each position, 3 replications were taken to decrease noise. The pruning weight (kg/tree) was measured on each experimental plot after mechanical pruning in July 2013. In addition, the visual canopy volume (VCV) parameter was measured, as defined in Escolà et al. (2017). It corresponds to the volume of a section of 2.2 m computed as the average of two central trees (a section of 4.4 m) of each study block. The olive harvest was carried out in November 2013, producing the oil by using the Abencor® system. Some oil quality parameters were analysed (stability, polyphenols, monounsaturated (MUFA) and polyunsaturated acids (PUFA)). Also, an organoleptic parameter (oil bitterness) was obtained by a hedonic test.

Statistical analysis

A multivariate analysis was performed between the PAR interception measurements, the Leafiness-LiDAR index and the canopy volume, yield and quality parameters obtained on each experimental plot, obtaining the matrix of Pearson's linear correlation coefficients and their significance by means of JMP Pro 14 software (SAS Institute Inc., Cary, USA).

Results

Multivariate descriptive analysis

Table 2 and 3 show the results of the multivariate correlation analysis between sensor-based measurements (PAR interception and Leafiness-LiDAR index; LLI) and yield and quality-related parameters. The highest positive correlations were obtained between LLI and PAR (r = 0.86) (Table 2 and Table 3). LLI was positively correlated to volume-related parameters: VCV and pruning weight (r = 0.80, r = 0.78), respectively. The lowest correlations were found between LLI, fruit yield and fruit dry matter (r = 0.47 and r = -0.48, respectively). LLI negatively correlated with stability, polyphenol percentage (r = -0.57) and bitterness (r = -0.59).

Table 2. Multivariate correlation analysis between the PAR interception, LLI, canopy valume and yield parameters. Bold font indicates statistical significance at p-value ≤0.001; (*) indicates significance at p-value ≤0.05.

	PAR (%)	**LLI** (m^2)	**VCV** (m^3/tree)	**Pruning weight** (kg/tree)	**Fruit Yield** (kg/tree)	**Fruit dry Matter** (kg/tree)
PAR (%)	**1**	**0.86**	0.55	0.58*	0.51	-0.65*
LLI (m^2)	**0.86**	**1**	**0.80**	**0.78**	**0.47**	**-0.48**
VCV (m^3/tree)	0.55	**0.80**	**1**	**0.79**	**0.50**	-0.36*
Pruning weight (kg/tree)	0.58*	**0.78**	**0.79**	**1**	0.34	-0.22
Fruit Yield (kg/tree)	0.51	**0.47**	**0.50**	0.34	**1**	**-0.52**
Fruit dry Matter (kg/tree)	-0.65*	**-0.48**	-0.36*	-0.22	**-0.52**	**1**

Table 3. Multivariate correlation analysis between the PAR interception, LLI and oil quality parameters. Bold font indicates statistical significance at p-value ≤0.001; (*) indicates significance at p-value ≤0.05.

	PAR (%)	**LLI** (m^2)	**Stability** (h)	**Polyphenols (**mg/kg**)**	**MUFA (%)**	**PUFA (%)**	**Oil bitterness**
PAR (%)	**1**	**0.84**	-0.22	-0.28	0.06	0.32	-0.24
LLI (m^2)	**0.84**	**1**	-0.57*	-0.59	-0.18	0.48	-0.59*
Stability (h)	-0.22	-0.57*	**1**	**0.92**	**0.72**	**-0.84**	**0.82**
Polyphenols (mg/kg)	-0.28	-0.59*	**0.92**	**1**	0.52	**-0.72**	**0.82**
MUFA (%)	0.06	-0.18	**0.72**	0.52*	**1**	**-0.91**	0.49
PUFA (%)	0.32	0.48	**-0.84**	**-0.72**	**-0.91**	**1**	-0.61*
Oil bitterness	-0.24	-0.59*	**0.82**	**0.82**	0.49	-0.61*	**1**

Discussion

Most studies found in the scientific literature used LiDAR technology for canopy density monitoring and LAI measurement (Arnó et al., 2013; Kargar et al., 2019; Mahmud et al., 2021). However, no studies were found concerning the relationship between structural and geometrical MTLS-derived parameters with PAR measurements. In addition, there is no LiDAR-derived index that serves as a measurement of geometric and structural parameters, such as porosity, together. In this respect, the results of the present study are encouraging, since a high correlation was found between the PAR measurements and the Leafiness-LiDAR index (r = 0.86). Furthermore, this index (LLI) had a similar

relationship (and more significance) with the yield and quality than the PAR measurements (Tables 2 and 3).
The statistical analysis showed a direct relationship between PAR and LLI values with fruit yield (kg/tree). Results also revealed an inverse relationship between yield with fruit dry matter (Table 2). These findings were also obtained by Connor et al. (2009) who concluded that there is no general relationship between fruit density and PAR intercepted by canopies. Nevertheless, other findings demonstrated the importance of high illumination for large fruit sizes and high oil content. For instance, Trentacoste et al. (2017) stablished that the light influenced oil accumulation and dry matter composition more strongly than water accumulation. Reale et al. (2019) stated that olives grown under well-lighting conditions influenced oil accumulation and dry matter composition and had larger mesocarp, concerning those grown at a low light intensity, and also had a higher percentage of oil and a lower water content. Nevertheless, Reale et al. (2019) also pointed out that fruit development is cultivar dependent. Since this study was conducted in an HD olive orchard, the fruit dry matter diminution could be related to light exposure.
Regarding oil quality, Proietti et al., (2012) established that the oil extracted from olives grown under greater light conditions had a higher polyphenol content and better sensorial characteristics than those obtained from olives grown at low light intensity. However, the results of the experiments (Table 3) revealed that those parameters related to good oil quality (stability, polyphenol content and oil bitterness) were inversely related to PAR and LLI. This fact could be attributed to the incident radiance on vertical walls. The study was carried out in an intensive olive orchard with 16NE-SW oriented rows. Nevertheless, as pointed out by Connor et al. (2009), E–W hedgerows have a distinct and stronger response to porosity compared to N–S hedgerows. Their analysis revealed direct relationships between fruit size, oil content and oil quality with light exposure in a 12 N-S cv. Arbequina SHD.
Olive intensification is associated with higher yield due to LAI increase. Mariscal et al. (2000) established that modern high-density planting orchards productivity is a function of their light interception. The analysis undertaken in this paper found evidence of these findings, since LLI and PAR measurements were positively correlated with yield. However, the increase of oil yield associated with the intensification of the olive grove does not always lead to the improvement or preservation of the quality of olive oil. Intensification, and particularly irrigation and nutrition, can affect vegetative growth, altering the characteristics of the leaf canopy in an undesirable way for olive yield and oil quality (Zipori et al., 2020). The results showed that with higher PAR and LLI, yield was larger, however, a high yield was negatively related to fruit dry matter and oil quality.

Conclusions

The Leafiness-LiDAR index (LLI) had a strong relationship with PAR measurements. Based on these findings, this index could be useful to estimate LAI in HD olive orchards not only from the early crop stages but also through the seasons by means of LiDAR-based MTLS. The findings presented in this paper, pointed that this index could be also useful to improve the balance between olive yield and oil quality. LLI index, could also be helpful to maintain productive canopies for longer periods, since good correlations were found between LLI and these parameters. LLI had a greater correlation with volume-related parameters than PAR measurements. This finding is very encouraging since light exposure constitute a limiting factor in SH and SHD systems and a continuous canopy management to optimize canopy light exposure represents a gap to bridge in those training systems management. Canopy volume control along seasons, may also help to adopt early decisions on pruning or fertigation as well as for variable input rate application in the framework of Precision Fructiculture. This study was based on data from an intensive olive orchard, but this methodology can be applied to other similar crops, being encouraging for regular monitoring and decision-making about precise fruit orchard management.

Acknowledgements

This work was carried out with data acquired in the project IRTA2012-00059-C02-01 funded by the Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria, as well as in the projects AGL2010-22304-C04-03 and AGL2013-48297-C2-2-R funded by the Spanish Ministry of Economy and Competitiveness and developed under the frame of the grants RTI2018-094222-B-I00 (PAgFRUIT project) and PID2021-126648OB-I00 (PAgPROTECT project) by MCIN/AEI/10.13039/501100011033 and by "ERDF, a way of making Europe", by the European Union.

References

Acebedo, M. M., Cañete, M. L., & Cuevas, J. (2000). Processes affecting fruit distribution and its quality in the canopy of olive trees. *Advances in Horticultural Science*, *14*(4), 169–175.

Arnó, J., Escolà, A., Vallès, J. M., Llorens, J., Sanz, R., Masip, J., et al. (2013). Leaf area index estimation in vineyards using a ground-based LiDAR scanner. *Precision Agriculture*, *14*(3), 290–306. https://doi.org/10.1007/s11119-012-9295-0

Cherbiy-Hoffmann, S. U., Hall, A. J., & Rousseaux, M. C. (2013). Fruit, yield, and vegetative growth responses to photosynthetically active radiation during oil synthesis in olive trees. *Scientia Horticulturae*, *150*, 110–116. https://doi.org/10.1016/J.SCIENTA.2012.10.027

Connor, D. J. (2006). Towards optimal designs for hedgerow olive orchards. *Australian Journal of Agricultural Research*, *57*(10), 1067–1072. https://doi.org/10.1071/AR05448

Connor, D. J., Centeno, A., Gómez-Del-Campo, M., Connor, D. J., & Centeno, A. (2009). Yield determination in olive hedgerow orchards. II. Analysis of radiation and fruiting profiles. *Crop and Pasture Science*, *60*(5), 443–452. https://doi.org/10.1071/CP08253

Connor, D. J., Gómez-del-Campo, M., Rousseaux, M. C., & Searles, P. S. (2014). Structure, management and productivity of hedgerow olive orchards: A review. *Scientia Horticulturae*, *169*, 71–93. https://doi.org/10.1016/J.SCIENTA.2014.02.010

Escolà, A., Martínez-Casasnovas, J. A., Rufat, J., Arnó, J., Arbonés, A., Sebé, F., et al. (2017). Mobile terrestrial laser scanner applications in precision fruticulture/horticulture and tools to extract information from canopy point clouds. *Precision Agriculture*, *18*(1), 111–132. https://doi.org/10.1007/s11119-016-9474-5

Gómez-Del-Campo, M., & García, J. M. (2012). Canopy fruit location can affect olive oil quality in "Arbequina" hedgerow orchards. *Journal of the American Oil Chemists' Society*, *89*(1), 123–133. https://doi.org/10.1007/s11746-011-1900-2

Kargar, A. R., MacKenzie, R., Asner, G. P., & van Aardt, J. (2019). A density-based approach for leaf area index assessment in a complex forest environment using a Terrestrial Laser Scanner. *Remote Sensing*, *11*(15). https://doi.org/10.3390/rs11151791

Mahmud, S., Zahid, A., He, L., Choi, D., Krawczyk, G., Zhu, H., et al. (2021). Development of a LiDAR-guided section-based tree canopy density measurement system for precision spray applications. *Computers and Electronics in Agriculture, 182,* 106053. https://doi.org/10.1016/j.compag.2021.106053

Pokovai, K., & Fodor, N. (2019). Adjusting ceptometer data to improve leaf area index measurements. *Agronomy*, *9*(12), 1–13. https://doi.org/10.3390/agronomy9120866

Proietti, P., Nasini, L., Famiani, F., Guelfi, P., & Standardi, A. (2012). Influence of light availability on fruit and oil characteristics in Olea europea L. *Acta Horticulturae*, *949*, 243–250. https://doi.org/10.17660/actahortic.2012.949.35

Reale, L., Nasini, L., Cerri, M., Regni, L., Ferranti, F., & Proietti, P. (2019). The influence of light on olive (Olea europaea l.) fruit development is cultivar dependent. *Frontiers in Plant Science*, *10*(March), 1–10. https://doi.org/10.3389/fpls.2019.00385

Rosati, A., Marchionni, D., Mantovani, D., Ponti, L., & Famiani, F. (2021). Intercepted Photosynthetically Active Radiation (PAR) and Spatial and Temporal Distribution of Transmitted PAR under High-Density and Super High-Density Olive Orchards. *Agriculture . 11 351*, *11*(4), 351. https://doi.org/10.3390/AGRICULTURE11040351

Schaefer, M. T., Farmer, E., Soto-Berelov, M., Woodgate, W., & Jones, S. (2015). Validation of LAI and F PAR products. In Held, A., Phinn, S., Soto-Berelov, M., & Jones, S. (Eds.). *AusCover Good Practice Guidelines: A Technical Handbook Supporting Calibration and Validation Activities of Remotely Sensed Data Products,* pp 88-118. (Queensland, Australia): TERN.

Trentacoste, E. R., Moreno-Alías, I., Gómez-del-Campo, M., Beyá-Marshall, V., & Rapoport, H. F. (2017). Olive floral development in different hedgerow positions and orientations as affected by irradiance. *Scientia Horticulturae*, *225*, 226–234. https://doi.org/10.1016/j.scienta.2017.06.029

Zipori, I., Erel, R., Yermiyahu, U., Ben-gal, A., & Dag, A. (2020). Sustainable management of olive orchard nutrition: A review. *Agriculture (Switzerland)*, *10*(1), 11. https://doi.org/10.3390/agriculture10010011